Fermilab

http://www.fnal.gov

Abort Gap Cleaning at LHC

Contents:

- Abort Gap Cleaning:
  - Simulations with MAD-X
  - Simulations of RF noise and cleaning process
  - Simulations with Synchrotron Radiation
- 2009 Operation:
  - Highlights
  - Test of AGC with beam

presented by Eliana GIANFELICE

Introduction

Particles not captured by the RF system at injection or leaking out of the RF bucket may quench superconducting magnets during beam abort.

The problem is particularly serious for LHC due to the very large energy stored in the beam. At 7 TeV with nominal current of 0.5 A (ie 1.15e11 particles per bunch in 2808 bunches) the beam energy is 362 MJ.

The abort kicker rise time is 3 μs (900 m); a corresponding long particle-free gap is needed for a clean beam dump.

Critical line density in the Abort Gap: 1e9 p/m at 450 GeV and 1e7 p/m at 7 TeV.

At LHC a way of removing the unbunched beam has been considered which uses the existing damper kickers to excite resonantly the particles traveling along the abort gap.

There are 4 dampers per transverse plane and beam, each providing a maximum kick of 0.5 μrad at 450 GeV.

Other machines

HERA-p:

- In normal conditions, coasting beam was not a "safety" issue. Few mA coasting beam cumulated over several hours (up to 24) posed a problem mainly to HERA-b.
- A resonant extraction of the coasting beam was tried, but the limited bandwidth of the power amplifier finally caused some emittance growth of the head bunches. It was never operational.

Tevatron:

- Coasting beam in the AG was a concern at the beginning of Run II.
- The use of the electron lens, first conceived for beam-beam compensation, decreased the cleaning time from 20 to 2 minutes eliminating the problem.

RHIC:

- Different production rates depending on operation.
- Cleaning is done with the tune kickers.
- Not always successful. CB responsible for about 3% of quenches during abort.

AGC MAD-X Simulations

- MAD-X thin lenses tracking module has been modified (by A. Koschik, 2007) to allow for time varying kicks.
- The process of filling the AG is *not* simulated. A given starting 6D distribution is specified at the beginning.
- The kick frequency program is specified through *macros*.

AGC at injection and at 7 TeV (luminosity optics) was studied with MAD-X. The movable collimators where introduced in the lattice and set at their nominal positions.

E (TeV)	ϵ_T (nm)	$\hat{\epsilon}_T$ (nm) (coll.)	V (MV)	bucket h.	σ_p	$\frac{\hat{\Delta p}}{p}$ (coll.)
0.45	7.30	240	8	1.0e^{-3}	4.3e^{-4}	3.6e^{-3}
7.00	0.47	16	16	3.6e^{-4}	1.1e^{-4}	1.7e^{-3}

Nominal Injection Optics

Preliminary tests were done with the nominal injection optics, 450 GeV.

400 particles extracted from a 6D Gaussian distribution (5 sigma cut) with

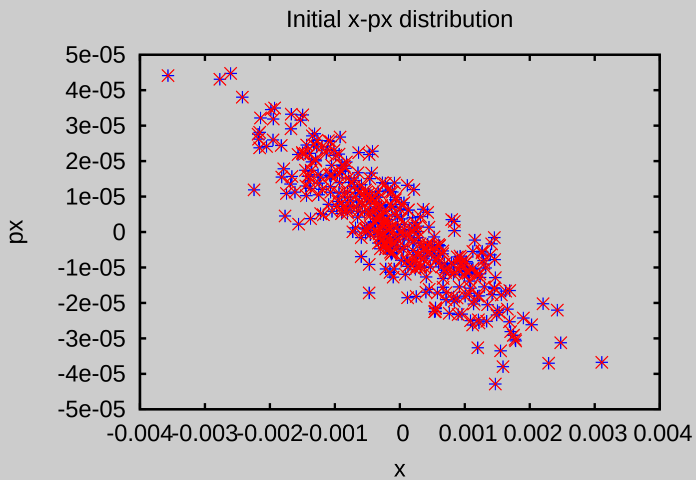
- $\boldsymbol{\epsilon_x}$=$\boldsymbol{\epsilon_y}$=7.3e-9 m (at 450 GeV) ie $\boldsymbol{\sigma_{x\beta}} \simeq \boldsymbol{\sigma_{y\beta}}$=1 mm at TCP.6L3.B1
- $\boldsymbol{\sigma_t}$=0.135 m, $\boldsymbol{\sigma_{dp/p}}$=4.3e-4

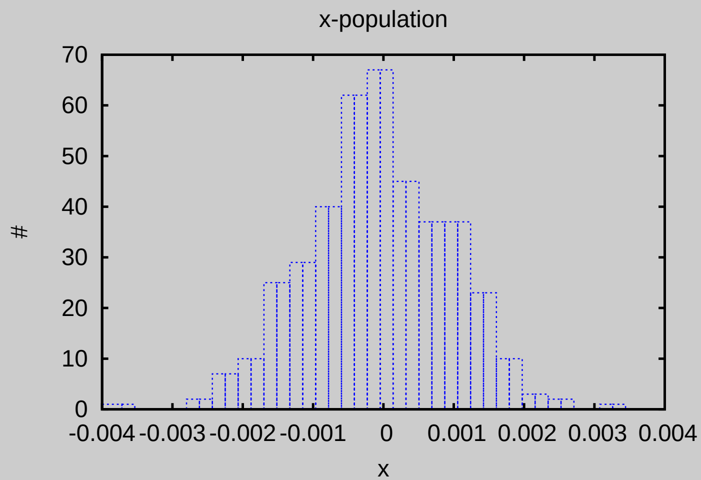
Dampers:

- $\hat{\boldsymbol{\theta}}$ = 0.05 $\boldsymbol{\mu}$rad per each of the 4 vertical dampers (almost scalable to 7 TeV)
- $\boldsymbol{\theta_n} = \hat{\boldsymbol{\theta}} \times \cos 2\pi n q_y$ ($\boldsymbol{q_y}$=0.31 $\longrightarrow$ $\boldsymbol{f_{damper}}$=3.5 KHz)

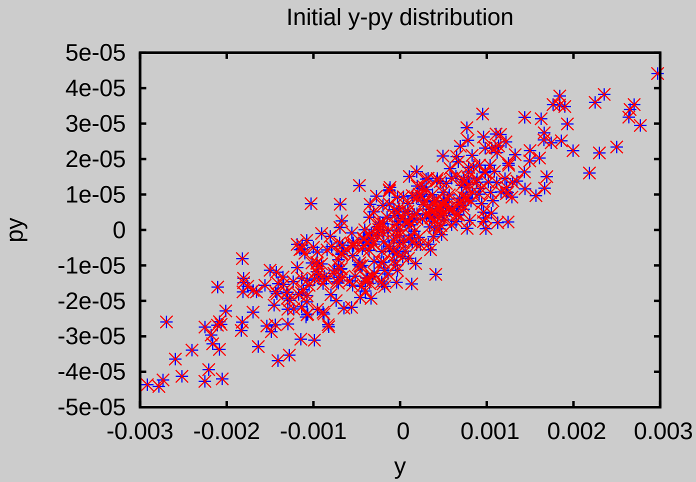
Blue: starting coordinates

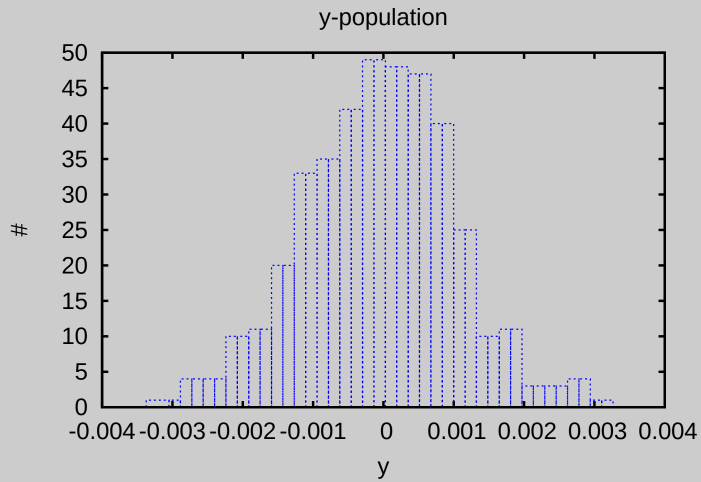
Red: starting coordinates of particles going to be lost.



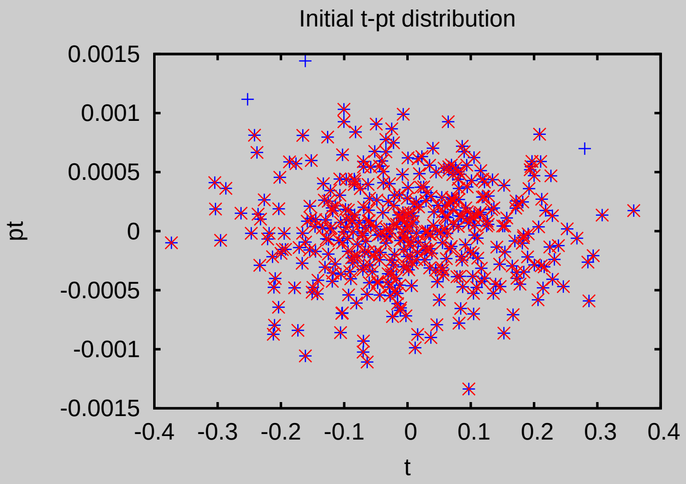


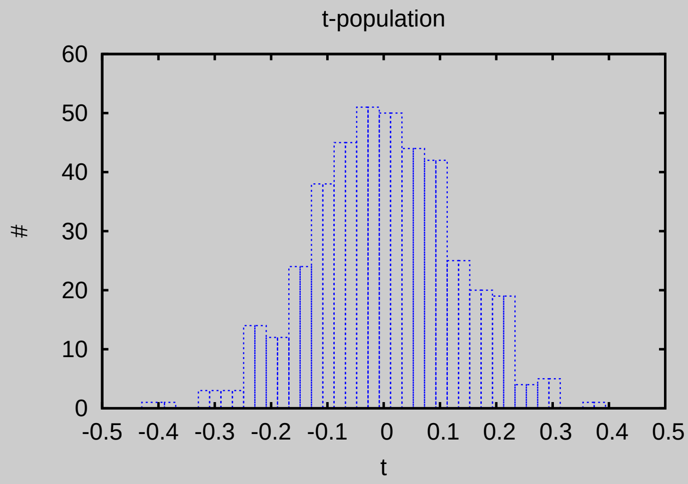
Fit: $\boldsymbol{\sigma_x}$=1.25 mm





Fit: $\boldsymbol{\sigma_y}$=1.16 mm



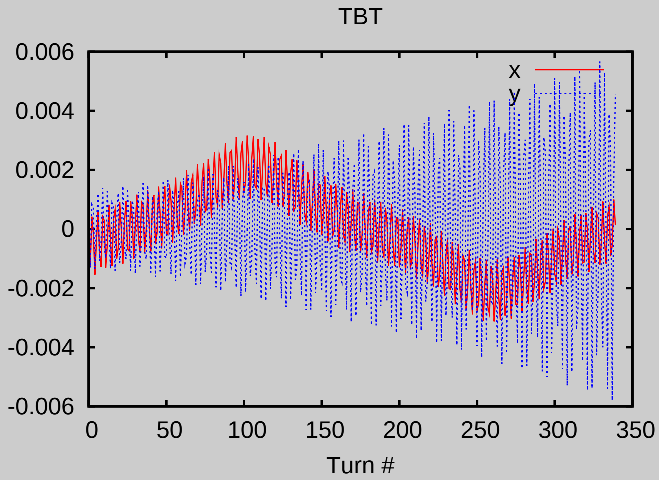


Fit: $\boldsymbol{\sigma_t}$=0.137 m, $\boldsymbol{\sigma_{dp/p}}$=0.00050

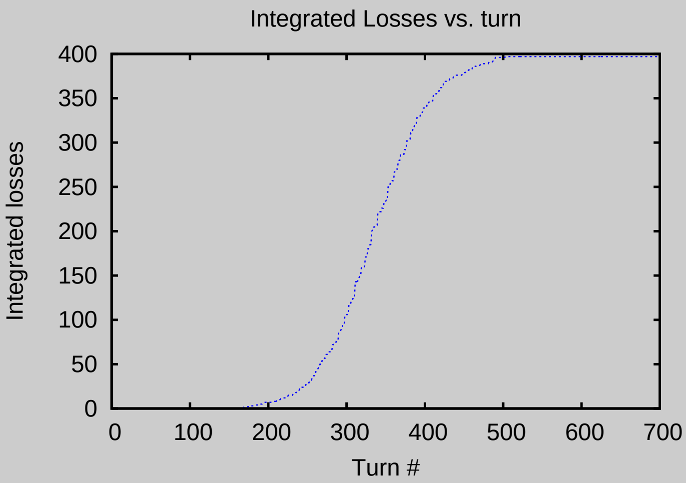
Three particles (outside the separatrix) are *not* kicked out![a]

[a]with reduced kick size wrt maximum!

TBT (for a particle close to the separatrix)



Integrated Losses



Particles lost at TCP.D6L7.B1 (vertical collimators set at 5.7 σ) as expected.

Injection Optics with errors

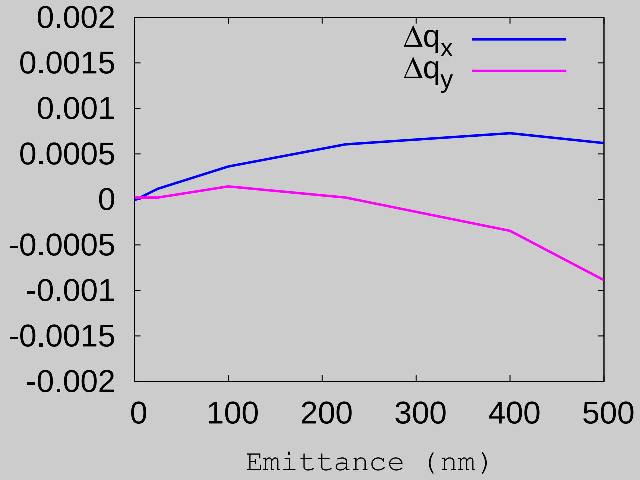
The *actual* distribution of particles in the AG will have dp/p up to 3.6×10^{-3}, limited by the momentum collimator TCP.6L3.B1 (ie 8 σ_p).

In presence of errors one can expect a larger dependence of tunes on *momentum* and *amplitude*.

- The number of tracked particles was increased to 2000 and their momentum spread increased artificially by a factor 3.
- The *measured* field errors where introduced in the optics. Random errors were added to account for measurement errors, while for the magnets not yet measured, statistical estimate were used.
- Systematic and empirical corrections were applied.

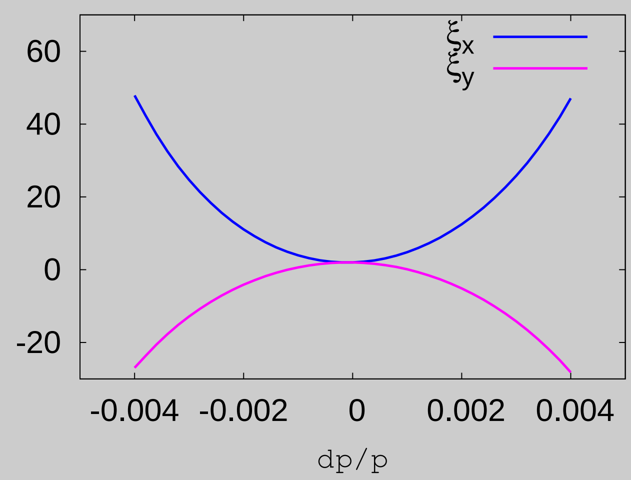
By using the *full* kick strength it is possible to kick all particles out when using the *vertical* dampers, while 1.9% survives the excitation with the *horizontal* ones (fixed frequency).

Tune change vs. amplitude



$\hat{\epsilon}_T$=240 nm

Chromaticity vs. momentum



$\Delta\hat{p}/p$=3.6e^{-3}

For *this* machine realization:

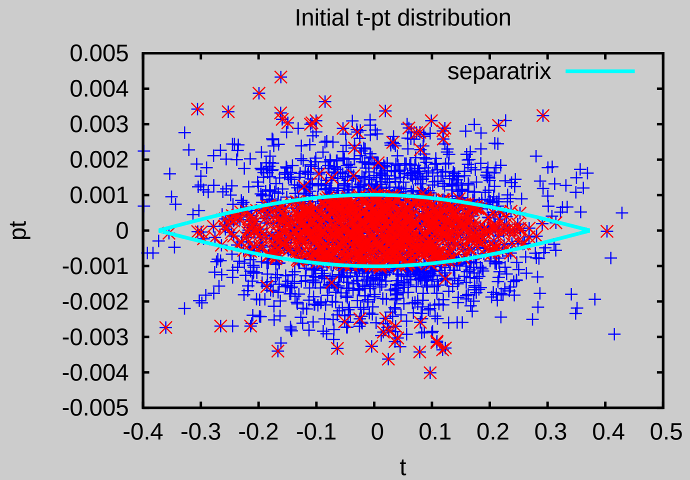
- The larger efficiency of the vertical dampers is consistent with the dependance of tunes on momentum
- Tune dependence on amplitude is small.

Using different seeds for the random part of the errors confirmed these conclusions.

What happens if for some reason the maximum kick cannot be applied or if the *actual* machine is not as linear as in the model?

Some tests were done by using a *reduced* kick ($\hat{\boldsymbol{\theta}} = 0.05\ \boldsymbol{\mu}$rad per damper).

Starting distribution

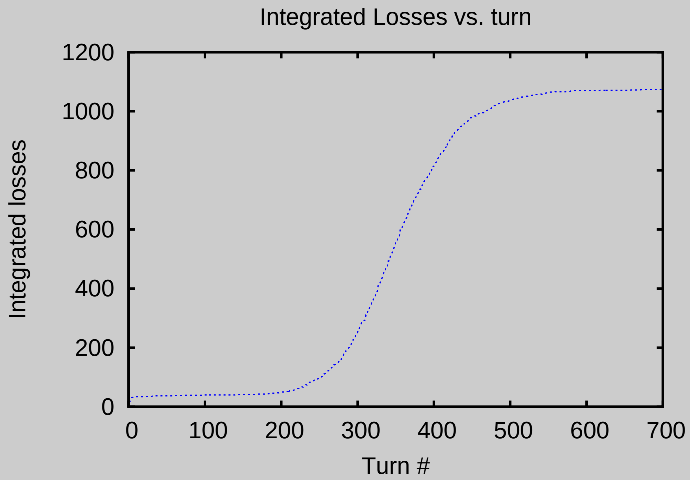


Particles in blue survive the 62 ms long burst at $\boldsymbol{f_{exc} = 0.31}$. The large momentum offset particles are intercepted by the momentum collimator TCP.6L3.B1.

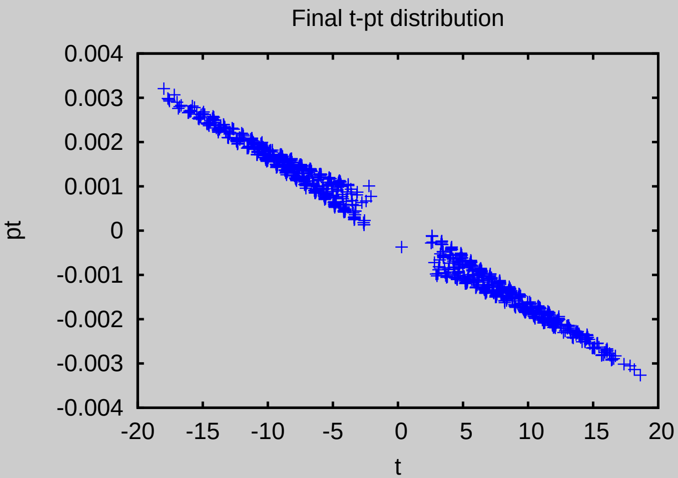
1074 particles are lost.

A longer excitation doesn't help: the core is lost between 200 and 500 turns.

Losses with f_{exc}=0.31



Final distribution



Try *alternative* damper excitations.

White Noise

- at each turn a number, a, between 0 and 1 is randomly extracted from a uniform distribution
- set $q_{exc} = q_1 + [q_2 - q_1] \times a \quad ([q_1, q_2] =$ frequency window)
- $K_n = \hat{V}_0 \times \cos\phi_n, \quad$ with $\phi_n = \frac{2\pi}{T}\int_0^{nT} q_{exc}(t)dt = 2\pi\Sigma_{i=1}^{n} q_{exc}^{i}$

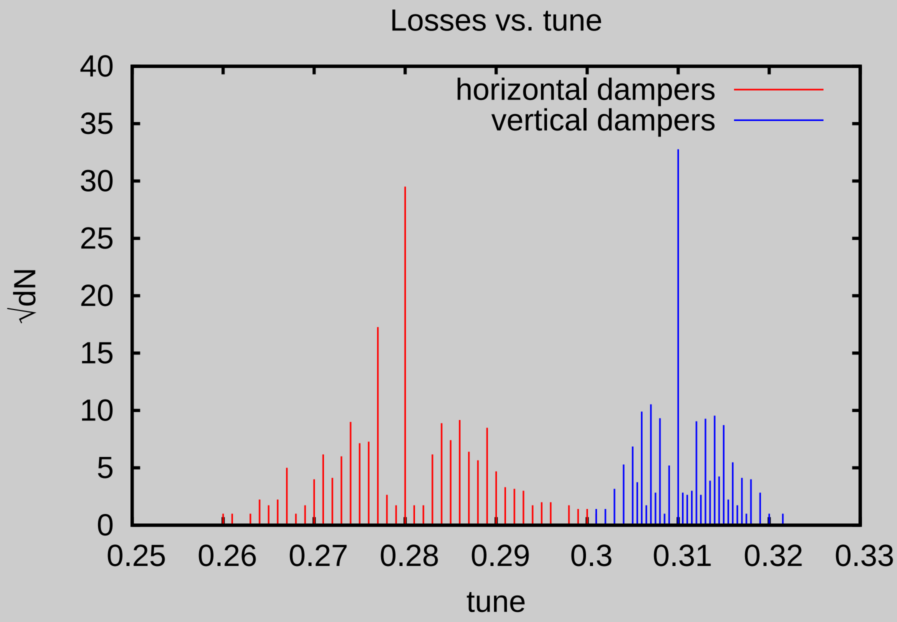
In the window [.298,.322] 1081 particles were lost from the *core* of the longitudinal distribution in 700 turns. It improves by increasing the number of turns.

Bursts of kicks (each at fixed frequency)

20 bursts, each 700 turns long, with frequency ranging between .301 and .322 (steps of 0.001): 0.6 % particles survived. For the remaining particles I tried finer steps (.0005) and I increased the range (0.286-0.336). Finally only *one* particle survived.

With the idea that the problem are the off-energy particles, I tried using the *horizontal* dampers to combine betatron amplitude and large offsets at $D_x \neq 0$ locations. The results were not as good as I expected. Losses are more spread out (consistent with dependence of tunes on momentum). With 50 steps of 0.001 starting from q_x=0.258 *all* particles are kicked out (those with large dp/p are lost at TCP.6L3.B1 as expected).

Losses (square root) vs tune



In conclusion for kicking *all* particles out of the gap by the horizontal dampers one would need about 35000 turns $\times$ 89 μs $=$ 3 seconds. [a]

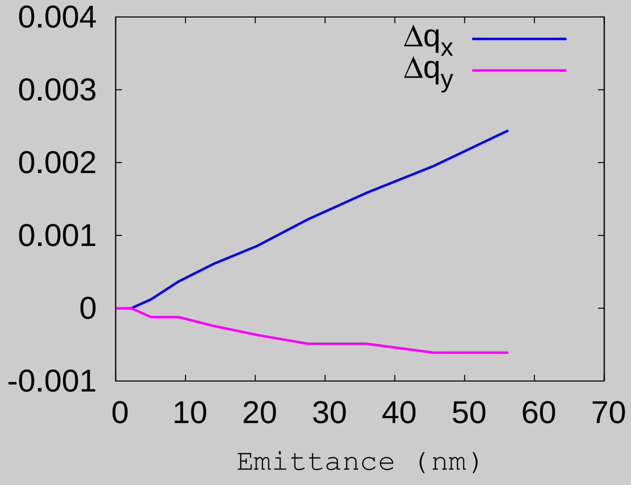
---

[a] for 5% capture losses it takes about 20 s to fill the AG in front of the first batch with about the critical density.

Luminosity Optics (with errors), 7 TeV

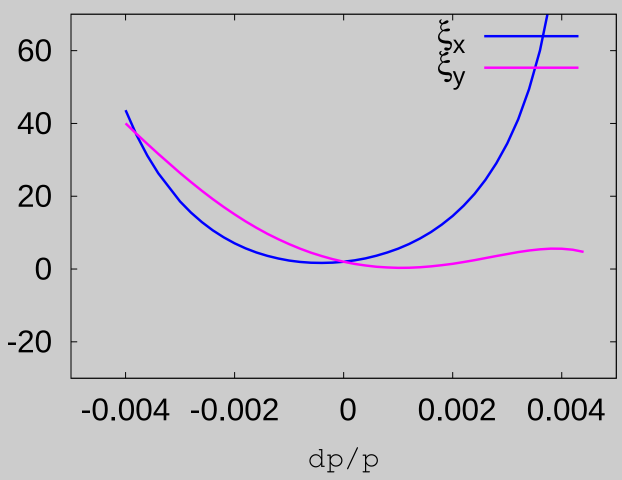
- Kicker strength decreases $(1/\gamma)$.
- Beam dimension decreases $(1/\sqrt{\gamma})$ ie the collimators are *physically* closer to the center.
- The smaller beam is less prone to non-linearities.

Tune change vs. amplitude



$\hat{\epsilon}_T$=16 nm

Chromaticity vs. momentum



$\Delta\hat{p}/p$=1.7e^{-3}

The coordinates of 2000 particles were extracted from the 6D gaussian distribution with $\boldsymbol{\sigma_{\mathrm{p}}}$ increased by a factor 6. Only particles with $\boldsymbol{\Delta p/p} < 0$ were kept (the scenario expected during luminosity operation) and, to speed up the computation, only particles outside the separatrix.

By kicking, with full strength (0.032 μrad per damper), at a frequency corresponding to the nominal vertical tune, namely 0.32, 72% of the particles are kicked out within 250 turns. The remaining particles could be removed in four steps, covering the range 0.315-0.319, within the first 250-300 turns.

If the horizontal dampers are used instead and modulated with a frequency corresponding to the nominal horizontal tune (0.31 at luminosity) all particles are kicked out within the first 250 turns. The horizontal dampers are in this case more efficient. This is due to the very small horizontal chromaticity for negative $\boldsymbol{\Delta p/p}$ within the momentum aperture $|\boldsymbol{\Delta p/p}| < \mathbf{1.7 \times 10^{-3}}$.

Abort Gap population simulation (450 GeV)

MAD-X simulations are relatively time consuming; for instance, tracking of 2000 particles over 1200 turns takes about 7 hours.

Including the population of the AG process is (was) not straightforward.

From MAD-X simulations one learns that, for the LHC AG Cleaning, main concern is the tune dependence on momentum.

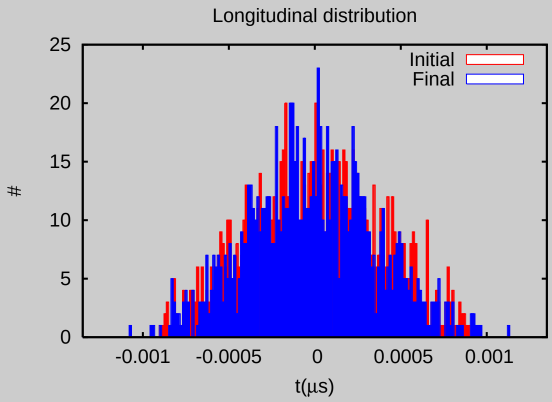
A simple tracking code, which includes the population of the AG process, was therefore written.

- Bunches with gaussian or uniform longitudinal distribution can be generated.
- White noise (amplitude and phase) may be added to the RF.
- Cleaning kicks may be applied when a particle crosses the AG. Particle oscillation amplitude and phase and position at the betatron and momentum collimators are computed.
- Tune dependence on momentum is accounted by using a previously prepared table.

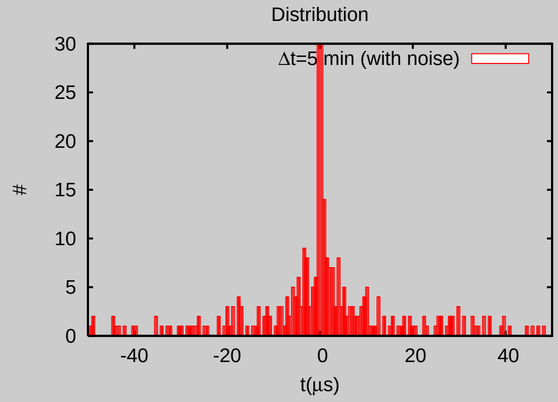
RF noise: 0.1 degree (phase)

1 V (amplitude) ie $\Delta V/V$=0.125e-6

1000 particles tracked over 5 minutes.

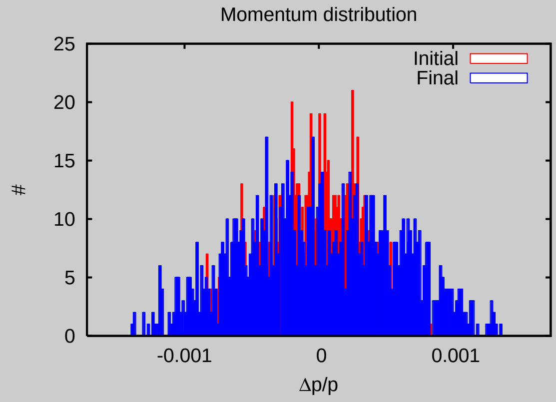


without noise



with noise[a]

[a] nb: larger bin width...



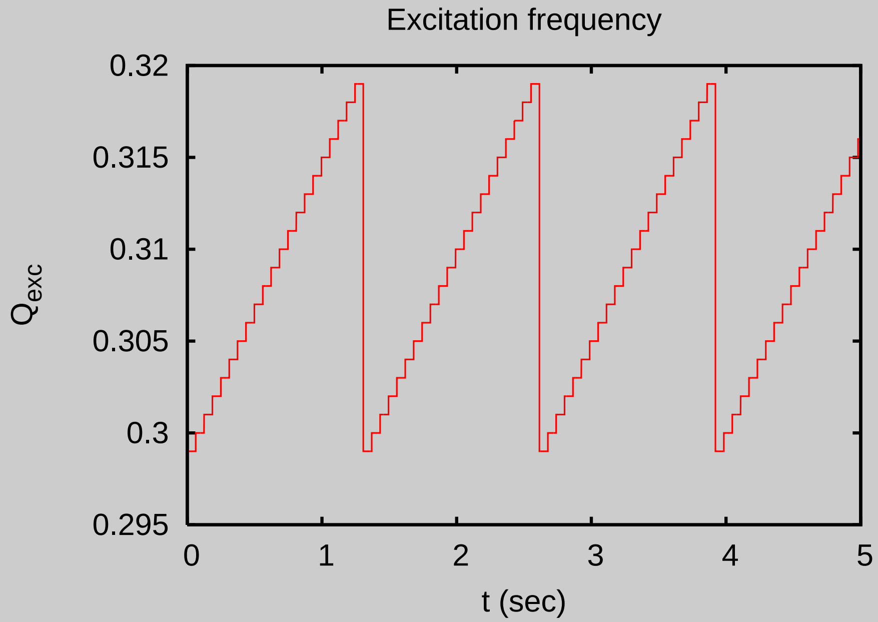
with noise[a]

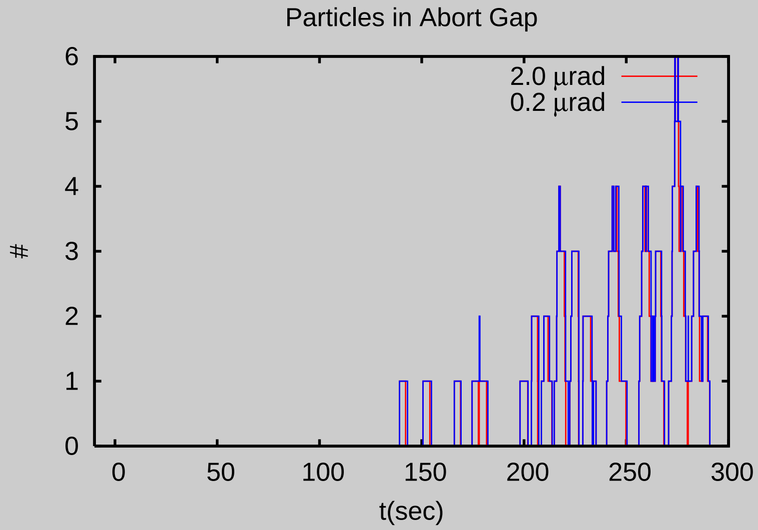
[a] none reaches the p-collimator!

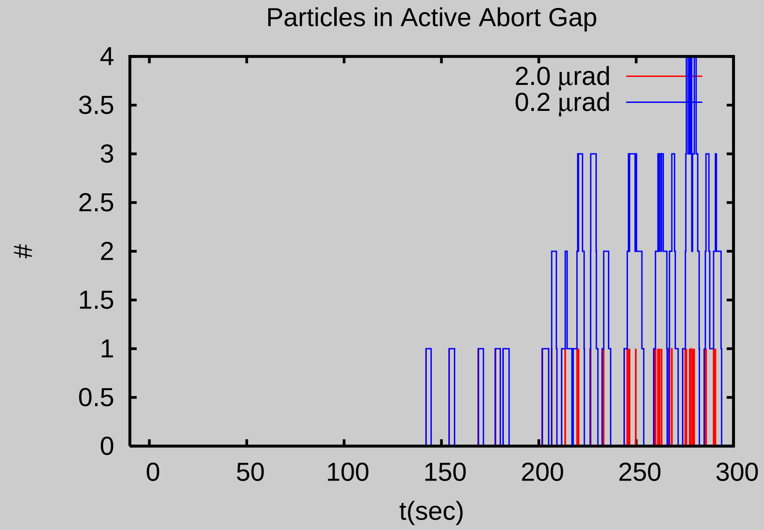
With noise, particles leak into the AG (the region beyond ±42.96 μs). Rate with assumed noise parameters: 1.6 p/sec, ie after 5 minutes about 50% of the particles are out of the bucket. Clearly too large...

Repeat tracking with RF noise and with dampers controlled so to clean 30% of the actual AG, with maximum kick of 2 and 0.2 μrad.

Frequency program: from 0.299 and 0.319 in 20 steps each 700 turns long.







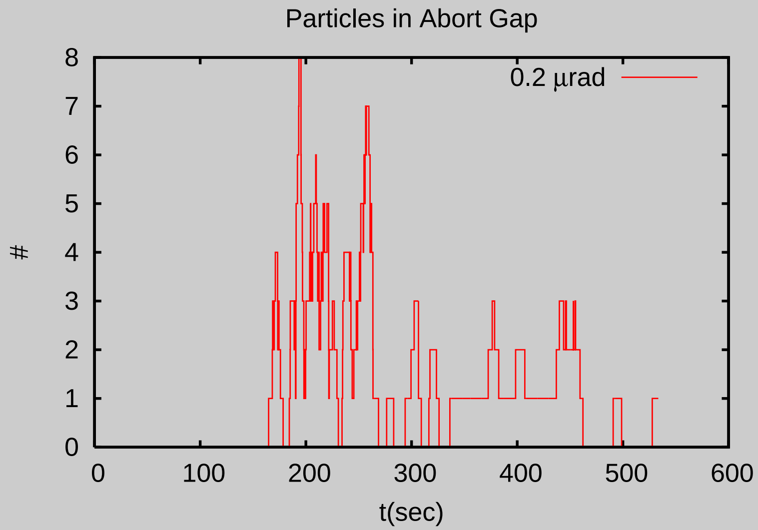
Population in the AG

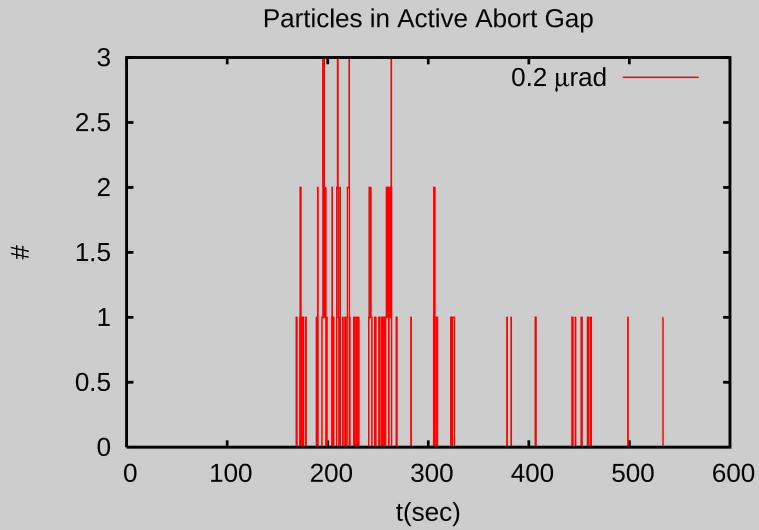
Population in the "active" AG

Repeat with: 5000 particles

smaller phase noise (0.01 degree $\longrightarrow$ 0.11 particles/sec)

$\hat{\boldsymbol{\theta}}$=0.2 $\boldsymbol{\mu}$rad





Population in the AG

Population in the "active" AG

It looks as the cleaning procedure considered here should work...

Influence of Synchrotron Radiation

Synchrotron Radiation is not negligible at 7 TeV. The energy lost per turn is about 6.5e-6 GeV. Effects of SR on the Abort Gap population/cleaning:

- An un-trapped particle loses energy through SR and reaches the maximum dp/p set by the collimators in about 160 s. This is a relatively long time and active cleaning may be still required.
- Un-trapped particles generated far from the AG, will have low momenta when reaching the AG and their tunes, depending on the non-linear chromaticity for $dp/p<0$ may be quite different from the nominal one.

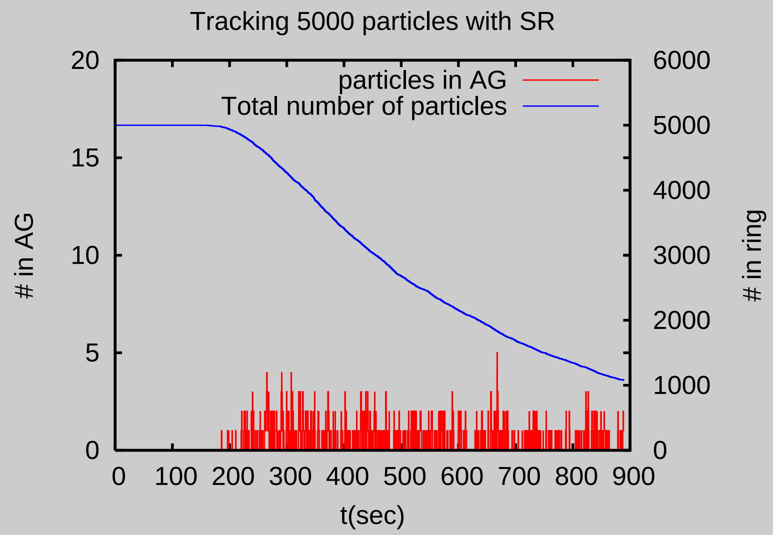
I made two sets of simulations under the following conditions

- one bunch containing 5000 particles with nominal longitudinal distribution is placed in the middle of the ring, ie at ±17820 buckets from the center of the AG (h=35640)
- one bunch containing 5000 particles with nominal longitudinal distribution is placed close to the AG (bucket number 17000).

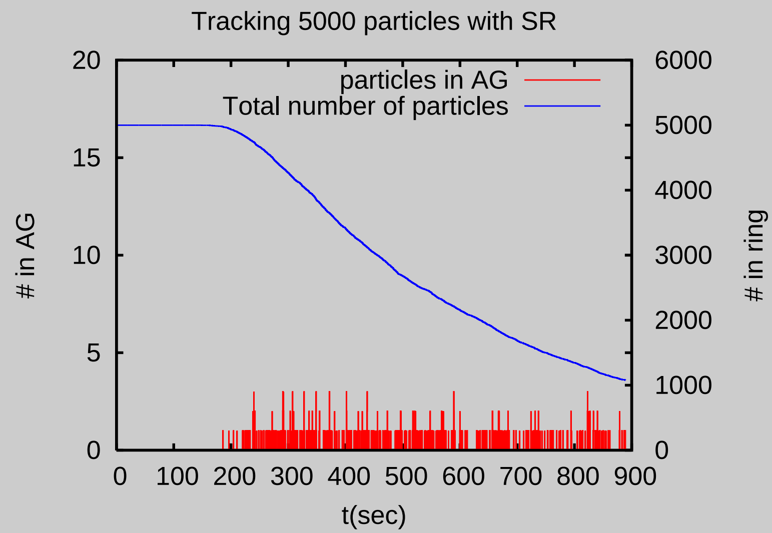
RF noise is introduced to get particles out of the bucket: with a phase noise of 0.1 degree one get a diffusion rate of 17 particles per second.

Tracking is done in presence of SR, without and with active cleaning of 100% of the AG with $\hat{\theta}$=0.128 μrad (maximum kick at 7 TeV).

Bucket #1



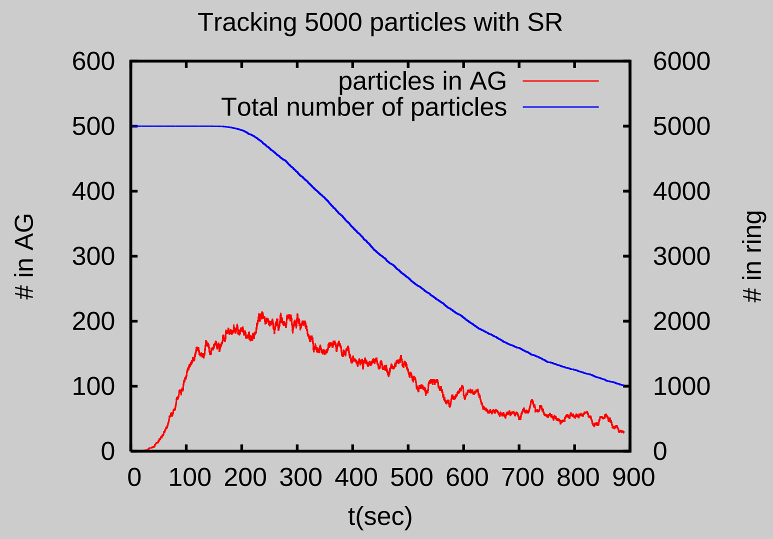
Population in ring and AG w/o cleaning

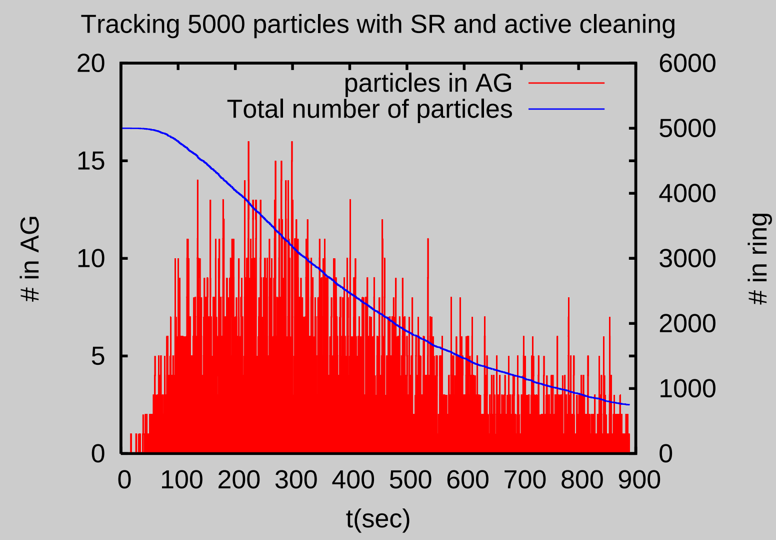


Population in ring and AG with cleaning

Frequency range: [0.298,0.320]

Bucket #17000





Population in ring and AG w/o cleaning

Population in ring and AG with cleaning
Frequency range: [0.30,0.32]

At 7 TeV, SR radiation offers a natural cleaning for buckets far from the Abort Gap. Active cleaning seems necessary for a full machine.

Summary of 2009 Operation

Talks of the 2010 Evian Beam Commissioning Workshop may be found at http://indico.cern.ch/conferenceDisplay.py?confId=76921

Milestones 1/2

20th Nov	injection of both beam – rough RF capture
21st Nov	Beam 1 circulating
22nd Nov	Beam 2 circulating
23rd Nov	First pilot collisions at 450 GeV First trial ramp
26th Nov	Pre-cycle established Energy matching
29th Nov	Ramp to 1.08 TeV and then 1.18 TeV
30th Nov	Solenoids on
1st – 6th Dec	Protection qualified at 450 GeV to allow "stable beams"
6th Dec	Stable beam @ 450 GeV
8th Dec	Ramp 2 beams to 1.18 TeV – first collisions
11th Dec	Stable beam collisions at 450 GeV with high bunch intensities: 4 x 2 10^10 per beam

19/01/10 LHC commissioning 2009

Milestones 2/2

14th Dec	Ramp 2 on 2 to 1.18 TeV - quiet beams - collisions in all four experiments
14th Dec	16 on 16 at 450 GeV - stable beams
16th Dec	Ramped 4 on 4 to 1.18 TeV - squeezed to 7 m in IR5 - collisions in all four experiments
16th Dec	End of run

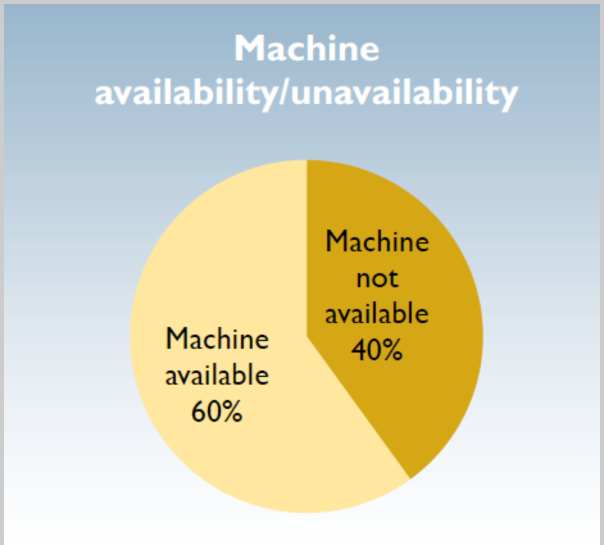
- 3 days - first collisions at 450 GeV
- 9 days – first ramp to 1.2 TeV
- 16 days - stable beams at 450 GeV
- 18 days - two beams to 1.2 GeV, first collisions

19/01/10 LHC commissioning 2009

(M. Lamont)

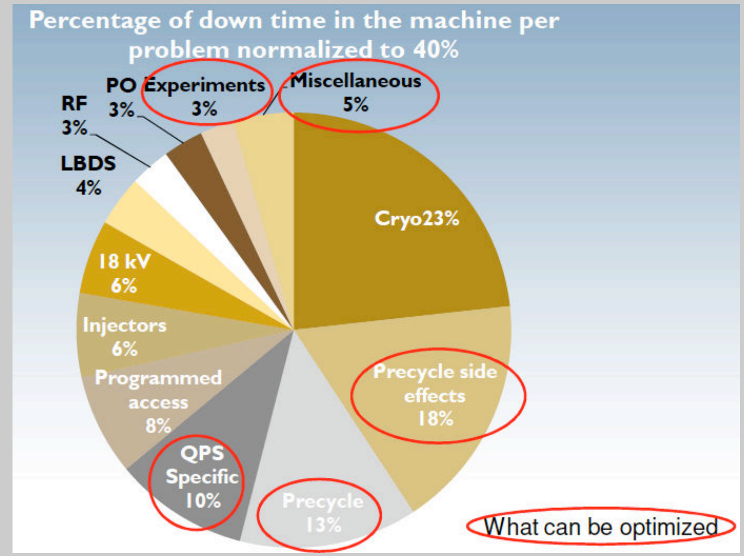
Availability

Reyes Alemany



29/01/10 Evian workshop summary

Unavailability



29/01/10 Evian workshop summary

(R. Alemany)

Beam Measurements vs. Magnet Model

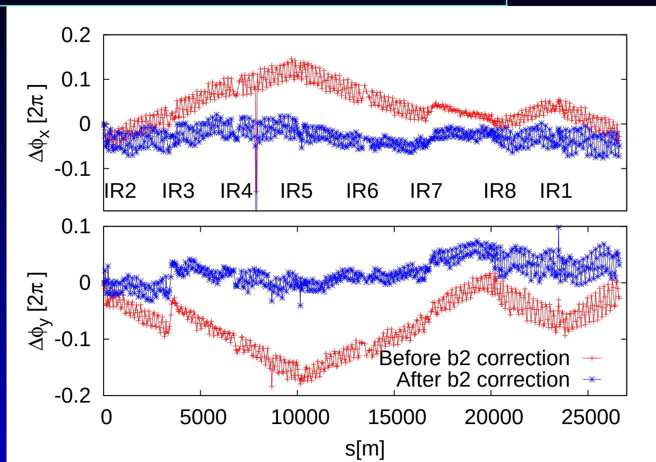
On the basis of the magnet field measurements and models, systematic corrections are applied. They performed overall well.

- Tunes: agreement within 0.1 with model. But large excursion of Q_x during ramp (especially B2) must be understood (b3 feed-down?).
- Chromaticity after ramp results under compensated. The (simplified) model used for estimating the “snapback” effect seems to be insufficient. It can be improved.

(E. Todesco)

Optics Measurements

Dipole b_2 correction - Beam 1



The magnetic dipole b_2 is used to compute the required correction with KQT $\rightarrow$ Excellent agreement!

LHC optics status summary

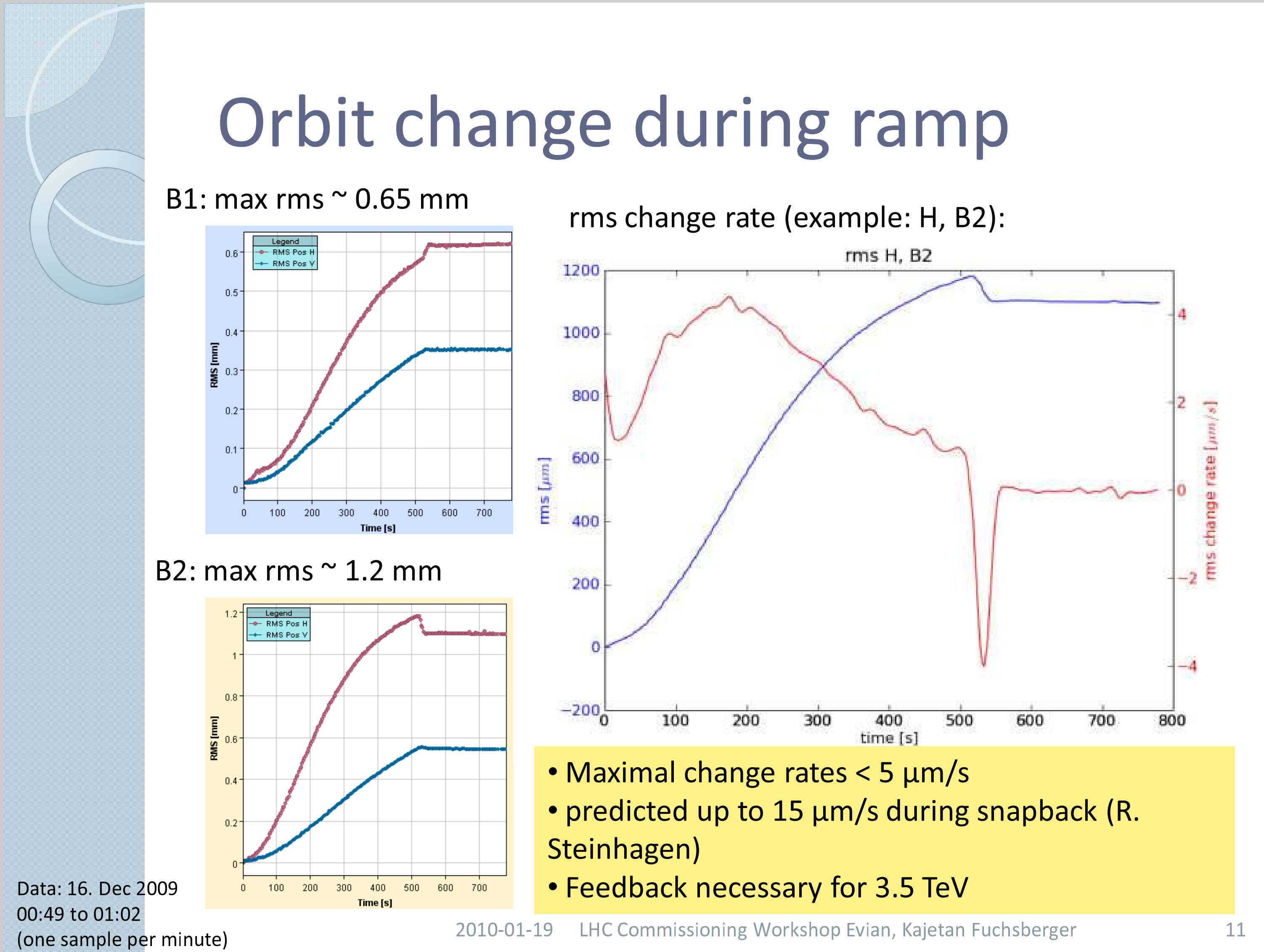
		Beam 1		Beam 2		Tol.
E	[TeV]	0.45	1.18	0.45	1.18	
$\Delta\beta_x/\beta_x$	[%]	35	20	40	15	14
$\Delta\beta_y/\beta_y$	[%]	50	16	55	20	16
$\Delta D_x^{qf}/D_x^{qf}$	[%]	19	11	16	?	30
$\Delta D_y^{qd}/D_x^{qf}$	[%]	8	12	11	?	28

Dispersion is within tolerances even at injection!

Large β-beating

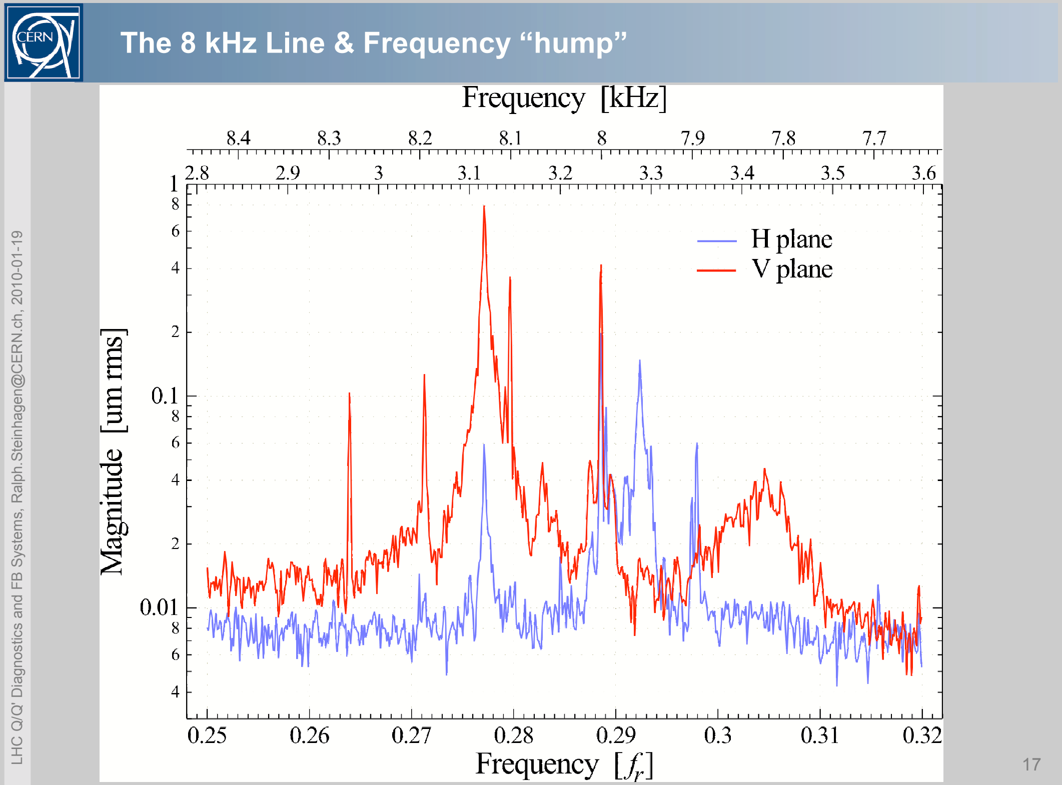
(R. Tomas)

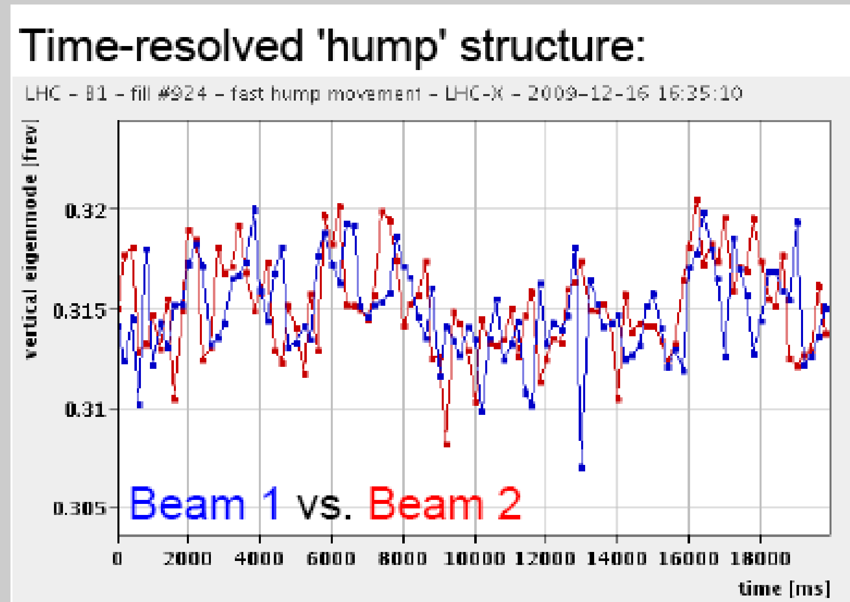
Attempts of localising sources and correcting optics distortions are on the way.



Feed-back will be tested in 2010. (K. Fuchsberger)

Disturbances in the Spectra





(R. Steinhagen)

8 KHz line likely due to the UPS.

Large “hump” close to nominal vertical tune: Alice spectrometer?

What went wrong...

Some operational issues must be solved before increasing intensity, for instance (from B. Goddard talk):

- Injection issues: accidental over-injections, injection when ring not yet ready for, beam injected and circulating while screens inserted.
- Sequencer should be made more robust against human mistakes. Too easy skipping/editing procedures.
- Chances (small) of injecting with unarmed LBDS.
- Tune feed-back "correcting" on noise after beam dump and messing up the machine.
- Erroneous dumps due to interlock BPMs.
- Information exchange between operators, experts and coordinators should be formalized.
- Poor communication with experiments.

AGC Preliminary Tests

The Abort Gap cleaning project is one of the task of the CERN TE/ABT group.

Persons, more or less, involved are W. Höfle, B. Goddard, M. Meddahi, V. Kahin, E. Shaposhnikova.

The monitoring of the AG population is done with a *synchrotron light detector* [a]. At 450 GeV it requires an *undulator*.

On the basis of the simulations, a study program for Abort Gap cleaning tests was prepared and submitted . Finally we got some hours during the last two days of operation (after undulator and BSRT commissioning for B2).

As the linearity of the machine is a crucial ingredient, I suggested to make a measurement of the non-linear chromaticity but I could not get it through...

[a] responsible: Alan Fischer (SLAC), LARP contribution

Cleaning of a bunched beam

- Cleaning of a *pilot* bunch with vertical dampers kicking at betatron frequency (0.266) with amplitude V=0.001 V_{max} [a]. Losses observed mainly at the TCP.D6L7.B the tightest vertical collimator, with a large shower at the horizontal collimator downstream. The test was repeated after increasing the voltage by a factor 3. The subsequent dump was not fully clean, indicating that *not* all particles had been kicked out.

- As above, but by changing the frequency in steps.

- As above but by changing the maximum voltage: losses increased/decreased accordingly.

[a] the actual value must be yet evaluated, for the moment the factor should be seen as relative just for comparing between the various experiments

Trailing edge

- Trailing edge effect studied by kicking at betatron frequency in the (empty) [a] middle of 2 bunches 3 μs apart. Large losses were observed for the *downstream* bunch with V=0.003 V_{max}.
- Scans of amplitude and "active" AG width were done in the attempt of finding an operational window. Only a drastic reduction of the voltage ($<$ 0.001 V_{max}, likely not useful for actual cleaning!) helped.

[a] in the meantime we had lost the AG monitor

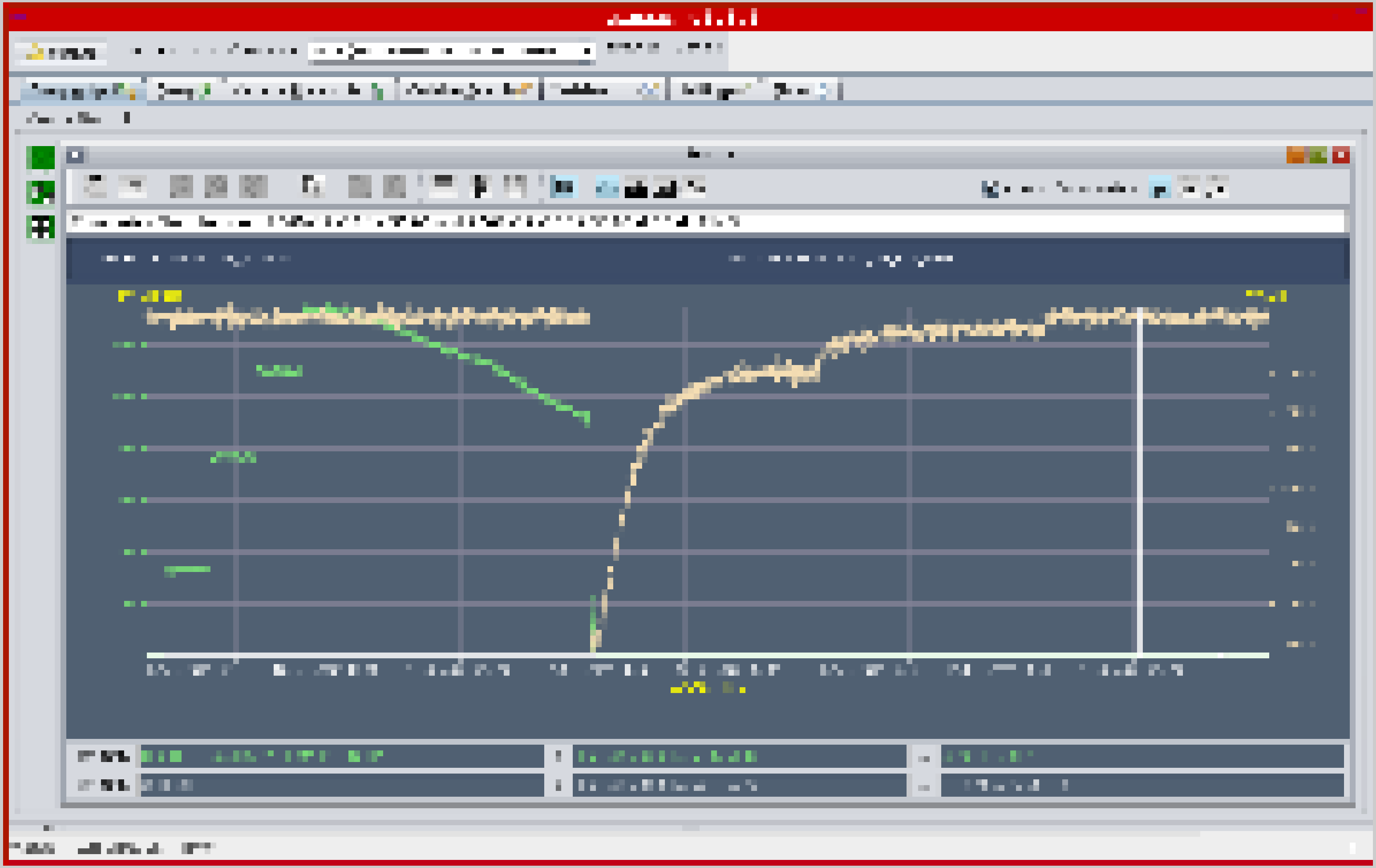
Cleaning of a coasting beam

- 2.5e10 protons were injected in 4 bunches, the RF switched off and after 5 minutes the cleaning of the Abort Gap started. 5 minutes cleaning of a coasting beam with $\boldsymbol{V}$=0.1 $\boldsymbol{V_{max}}$ and the frequency continuously ramped between .2 and .3 in 10 steps, each 100 turns long [a]. After 5 minutes of this procedure the beam was intentionally dumped. The dump was not clean and BLM signals showed that the procedure *failed* to clean the Abort Gap. The dump after a second experiment, w/o cleaning, showed same signature.

- The frequency program was changed according to simulation conditions, namely the excitation tune was varied between 0.299 and 0.319 in 20 steps each 700 turns long. The kick duration covered about 1/3 of the Abort Gap, ie 1 $\boldsymbol{\mu}$s, and the amplitude was $\boldsymbol{V}$=0.3 $\boldsymbol{V_{max}}$. The following dump showed that the procedure *succeeded* to clean the Abort Gap.

[a] nb: frequency program set *not* according to simulations!

In the meantime the AG monitor was working again.



Summary of AGC tests

- First tests done to check functionality.
- 2th experiment of cleaning of a coasting beam seems to confirm simulation results, namely the importance of the frequency program.
- Did the first one fail because the kick was too small or the frequency program was wrong?
- The magnitude of the actual kick must be understood (for comparing with simulations).
- Issue: trailing edge effect. It needs to be understood and solved!

Snap-back

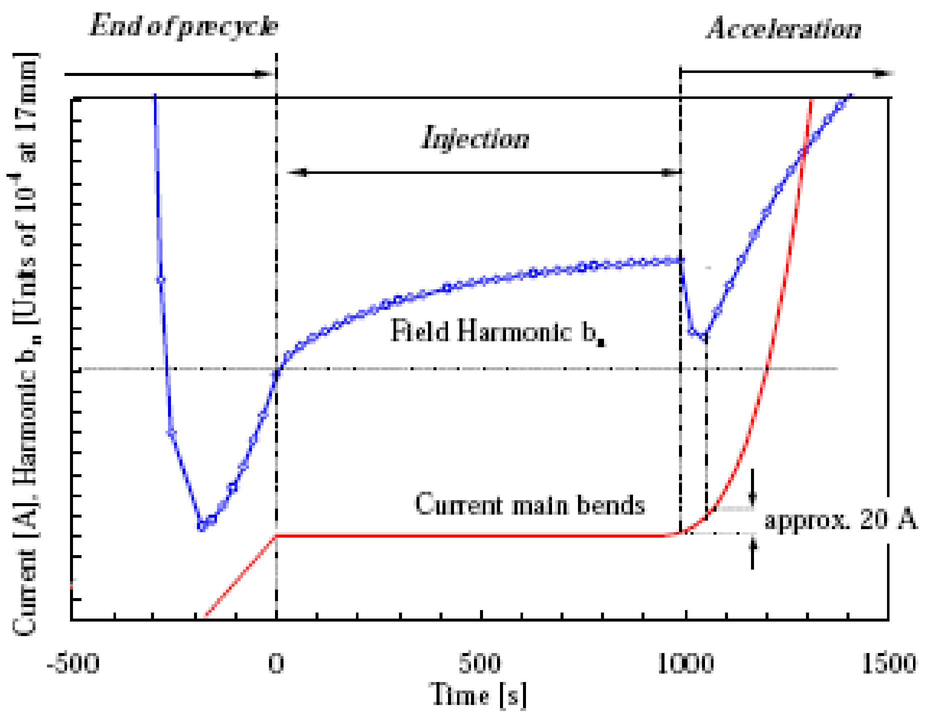


Figure 1: Example of the decay of a field error in a LHC dipole showing the current in the dipole and the evolution of the field error b_n as a function of time.

(T. Wijnands et al., EPAC2000)